EVALUATION OF EFFECTS OF RESPONSE SPECTRUM ANALYSIS ON HEIGHT OF BUILDING

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Abstract
The main aim of the proposed research is to provide guidelines for critical structure height above which Response Spectrum Analysis (RSA) significantly affects the structure design. Response spectrum analysis of 20 story building has been discussed in detail and comparison of static and dynamic analysis and design results of buildings up to 400 ft height (40story) in terms of percentage decrease in bending moments and shear force of beams, bending moments of columns, top story deflection and support reaction are presented in this paper. Percentage decrease in reinforcement area requirement for different members has also been discussed.

1. Introduction

After the devastating October 2005 earthquake in Pakistan, the building regulatory authorities reconsidered the existing structure design requirements for the area surrounding the Islamabad, Peshawar and Azad Jammu & Kashmir. Earthquake zoning of the area was changed and Islamabad, Peshawar and AJK were put under seismic zone III. Also dynamic analysis was made an essential part of structure design for the buildings to be constructed in seismic zone III. Two types of dynamic analysis can be used to make the structures sound against seismic activity. One is Time History dynamic analysis and the other is Response spectrum analysis. For Time History analysis, we do need a bunch of site specific data (period, amplitude) to define the required time history functions. On the other hand, to perform Response spectrum analysis, idealized response spectrum curves provided by UBC can be selected to use by providing seismic coefficients Ca and Cv of the respective seismic zone.

The requirement therefore emerges for a study that can provide guidelines for critical structure height above which response spectrum analysis significantly affects the structure design results and financial aspects of building construction so as to make the structure design process more efficient and to avoid extra effort on structures below that critical height.

First, a regular square building with five stories (50 feet) height was assumed which was supposed to be constructed in Islamabad. A typical Moment Resisting Framing system was used in the research with due consideration to local requirements. The above said structure was analyzed by using Static Lateral load method as well as RSA and structural members were designed against the most critical load combinations for both methods of analysis. Further, building height was increased by 5 stories (50ft) in each steps up to 40 stories (400ft) and were analyzed using both static and dynamic analysis methods.

2. Requirement of Dynamic analysis

Behavior of structure during an earthquake is basically a vibration problem. The seismic movement of the ground causes the structure to vibrate and causes structural deformity in the building. Different parameters regarding this deformity like frequency of vibration, time period and amplitude are of significant importance and defines the overall response of the structure. This overall response also depends on the distribution of seismic forces within the structure which again depends on the method which is used to calculate this distribution.

The lateral force requirements of UBC-97 suggest several methods that can be used to determine of the distribution of seismic forces within a structure.

Different methods of 3-Dimensional dynamic analysis of structures have become more efficient in use along with the development of technology. Response spectrum analysis method for seismic analysis is one of them which also can give more accurate results than an equivalent static approach. [1]

The major advantage of using the forces obtained from a dynamic analysis as the basis for a structural design is that the vertical distribution of forces may be significantly different from the forces obtained from an equivalent static load analysis. Consequently, the use of dynamic analysis will produce structural designs that are more earthquake resistant than structures designed using static loads.

3. Response spectrum analysis (RSA)

3.1. Response Spectrum

A response spectrum is simply a plot of the peak or steady-state response (displacement, velocity or acceleration) of a series of oscillators of varying natural frequency, that are forced into motion by the same base vibration or shock. The resulting plot can then be used to pick off the response of any linear system, given its natural frequency of oscillation. [2]

Response spectra are very useful tools of earthquake engineering for analyzing the performance of structures and equipment in earthquakes, since many behave principally as simple oscillators (also known as single degree of freedom systems). Thus, if you can find out the natural frequency of the structure, then the peak response of the building can be estimated by reading the value from the ground response spectrum for the appropriate frequency. In most building codes in seismic regions, this value forms the basis for calculating the forces that a structure must be designed to resist (seismic analysis). [2]

3.2. Description of (RSA) Procedure

RSA is an elastic dynamic analysis of a structure utilizing the peak dynamic response of all modes having a significant contribution to total structural response. Peak modal responses are calculated using the ordinates of the appropriate response spectrum curve which correspond to the modal periods. Maximum modal contributions are combined in a statistical manner to obtain an approximate total structural response. [3]

Important parameters required for performing RSA are as under

1. Ground Motion and representation of Response Spectrum
2. Modal Analysis
3. Method for combining Modal Maximum Responses
4. Scaling of Elastic Response Parameters
5. Directional Effects

3.3. Ground Motion and Representation of Response Spectrum

An elastic design response spectrum constructed in accordance with Figure 1.3, using the values of Ca and Cv consistent with the specific site. The design acceleration ordinates shall be multiplied by the acceleration of gravity, 386.4 in./sec^2 (9.815 m/sec^2). [3]

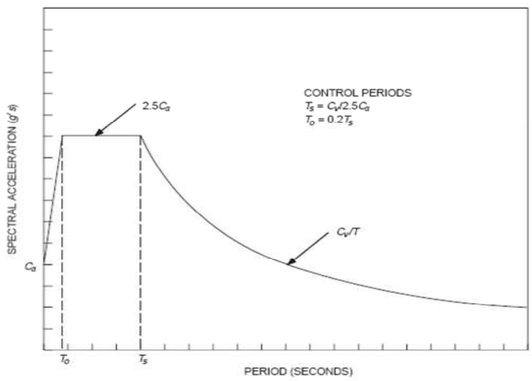

Fig.1: *Typical Response Spectrum Curve*

Most of the structural analysis software packages provide facility to get the response spectrum curve by entering values of Ca and Cv.

3.4. Modal Analysis

Modal analysis is the study of the dynamic properties of structures under vibration excitation. The goal of modal analysis in structural mechanics is to determine the natural mode shapes and frequencies of an object or structure during free vibration. Response Spectrum analysis requires to include the response of all significant modes to calculate the structure response. To satisfy this requirement number of modes considered should be such that, at least 90 percent of the participating mass of the structure is included in the calculation of response for each principal horizontal direction. [3] When vertical dynamic response of structural elements are required to be calculated e.g. vertical vibration of beams and floor systems and exact frequencies and mode shapes are used in the analysis , Ritz vector approach is recommended because for eigenvector analysis hundreds of modes will be required to capture 90% mass participation as is required by UBC-97[4].

3.5. The CQC method of modal combination

The most conservative method that is used to estimate a peak value of displacement or force within a structure is to use the sum of the absolute of the modal response values. Another very common approach is to use the Square Root of the Sum of the Squares, SRSS, on the maximum modal values in order to estimate the values of displacement or forces. [5]

The relatively new method of modal combination is the Complete Quadratic Combination, CQC, method [6] that was first published in 1981. It is based on random vibration theories and has found wide acceptance by most engineers and has been incorporated as an option in most modern computer programs for seismic analysis. Most of the structure analysis software provides all CQC, SRSS, ABS and GMC modal combinations methods as options. The use of CQC method is highly recommended to use for modal combination.

3.6. Scaling of Elastic Response Parameters

UBC-97 provides guidelines for scaling of response spectrum parameters in its clause 1631.5.4 which is as follows.

Elastic Response Parameters may be reduced for purposes of design in accordance with the following items, with the limitation that in no case shall the Elastic Response Parameters be reduced such that the corresponding design base shear is less than the Elastic Response Base Shear divided by the value of *R*.

1. For all regular structures where the ground motion representation complies with Section 1631.2 (Ground Motion Representation), Item 1, Elastic Response Parameters may be reduced such that the corresponding design base shear is not less than 90 percent of the base shear determined in accordance with Section 1630.2 (Static Force Procedure).

2. For all regular structures where the ground motion representation complies with Section 1631.2, Item 2, Elastic Response Parameters may be reduced such that the corresponding design base shear is not less than 80 percent of the base shear determined in accordance with Section 1630.2.

3. For all irregular structures, regardless of the ground motion representation, Elastic Response Parameters may be reduced such that the corresponding design base shear is not less than 100 percent of the base shear determined in accordance with Section 1630.2. [3]

The structural model that we have used for this research work falls in category 3. Detailed procedure for scaling of response spectrum parameters have been described in the next chapter.

3.7. Directional Effects

A weakness in the current code is the lack of definition of the “principal horizontal directions” for a general three dimensional structure. If an engineer is allowed to select an arbitrary reference system, the “dynamic base shear” will not be unique and each reference system could result in a different design. One solution to this problem that will result in a unique design base shear is to use the direction of the base shear associated with the fundamental mode of vibration as the definition of the “major principal direction” for the structure. The “minor principal direction” will be, by definition, ninety degrees from the major axis. This approach has some rational basis since it is valid for regular structures.[7] The required design seismic forces may come from any horizontal direction and, for the purpose of design, they may be assumed to act non-concurrently in the direction of each principal axis of the structure.

For the purpose of member design, the effects of seismic loading in two orthogonal directions may be combined on a square-root-of-the-sum-of-the-squares (SRSS) basis.[7]

4. Dynamic analysis of a 20 Story Building

As many structures with different stories heights are analysed. Therefore, in order to avoid the description of similarity of the work, in the following section, a comparative study of analysis and design results of dynamic and static analysis of only a 20 story building is presented.

4.1. *Description of Building*

The buildings considered for this research work are Commercial cum Residential buildings.

The first four floors will be considered as commercial with showrooms and display centers on two lower floors and studio apartments (Official Use) on upper two floors and live load will be assigned accordingly. All floors above first four, which will be added at different stages of this research will comprise of two bedroom residential apartments.

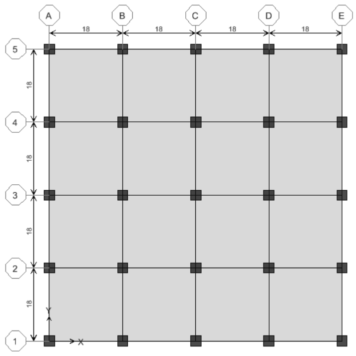

Fig.2: *Floor Plan of 20 Story Building*

4.2. *Earthquake load*

For static analysis seismic forces on the building will be determined in accordance with chapter 16 Div IV of UBC-97, Design provisions for earthquake resistance of structures.

Seismic zone:	Zone 3
Seismic zone factor:	Z = 0.3
Soil Profile Type	SD (Stiff Soil Profile)
Seismic Importance factor	Essential facility (I = 1.00)
Response Modification Factor	8.5 (For concrete MRF system)
Seismic Coefficient	Ca = 0.36, Cv = 0.54

4.3. *Response Spectrum Function*

In ETABS Spectrum function is selected as per UBC-97 against Ca=0.36 and Cv=0.54. The spectral values are as under.

Table 1: *Live Loads for the Structure*

Period	**Acceleration**	**Period**	**Acceleration**	**Period**	**Acceleration**
0.0	0.36	2.0	0.27	6.5	0.0831
0.12	0.9	2.5	0.216	7.0	0.0771
0.6	0.9	3.0	0.18	7.5	0.072
0.8	0.675	3.5	0.1543	8.0	0.0675
1.0	0.54	4.0	0.135	8.5	0.0635
1.2	0.54	4.5	0.12	9.0	0.06
1.4	0.3857	5.0	0.108	9.5	0.0568
1.6	0.3375	5.5	0.0982	10.0	0.054
1.8	0.3	6.0	0.09	-----	-----

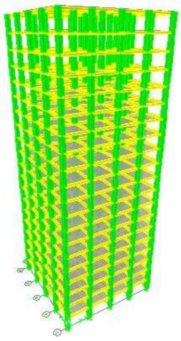

Fig.3: 3-*Dimensional extruded view of 20-Story Building*

5. Sample Beam Result Comparison

A typical bending moment diagram from level 10 is presented hereunder. In dynamic analysis a decrease of 31.3 % in negative bending moments and 46% decrease in positive bending moment, in comparison with static analysis, was observed.

In dynamic analysis a decrease of 35.6% in negative longitudinal reinforcement area was observed while the decrease in positive longitudinal reinforcement area was 50%

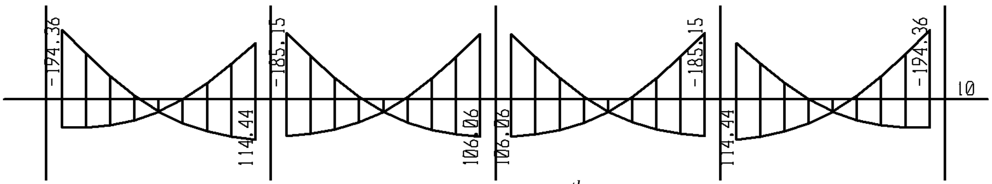

Fig. 4: *Bending Moment diagram of Beams at 10th story-Static analysis*

Fig. 5: *Longitudinal Reinforcement Detail of Beams at 10th story---Static analysis*

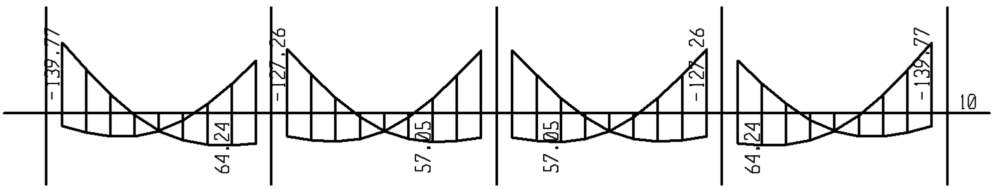

Fig. 6: *Bending Moment diagram of Beams at 10th story---Dynamic analysis*

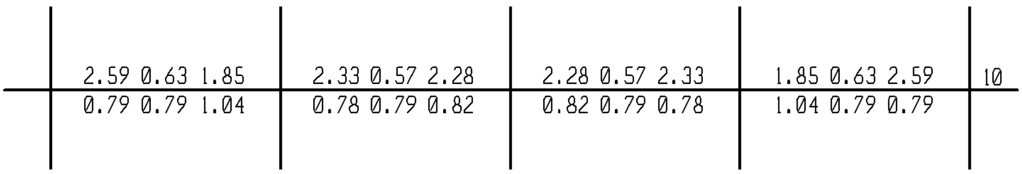

Fig.7: *Longitudinal Reinforcement Detail of Beams at 10th story---Dynamic analysis*

6. Summary of Result Comparison

Height of Building	Avg. Change in Beam Forces		Avg. Change in Column Forces	Avg. Change in Max. Deflection	Avg. Change in Support Reactions
	Bending Moment	Shear Forces			
60	2.2	1.25	1.46	6	1.78
100	8.53	4.24	1.64	17	1.82
150	16.15	10.35	3.66	27	3.66
200	31.3	21.7	18.9	44	18.90
250	33.2	24.8	16.04	45	16.00
300	37.8	29.456	20.8	48	20.94
350	35.6	29.2	15.8	45	15.84
400	42.1	36	26.5	50	26.60

Table 2: *Summary of comparison of member forces resulting from static and dynamic analysis*

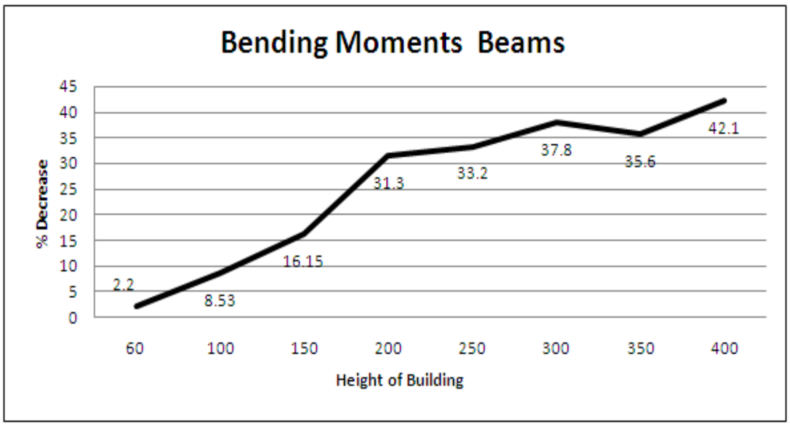

Fig. 8: *Graph showing percentage decrease in bending bending moment of beam Vs height of building*

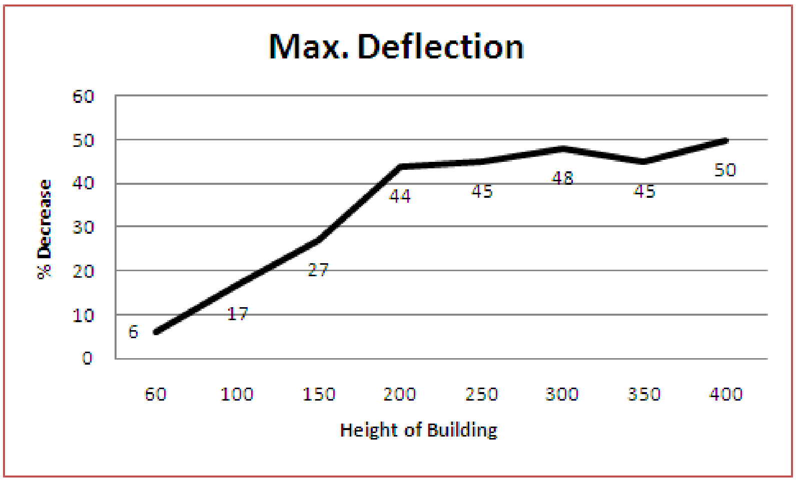

Fig. 9: *Graph showing % decrease in top story deflection Vs height of building*

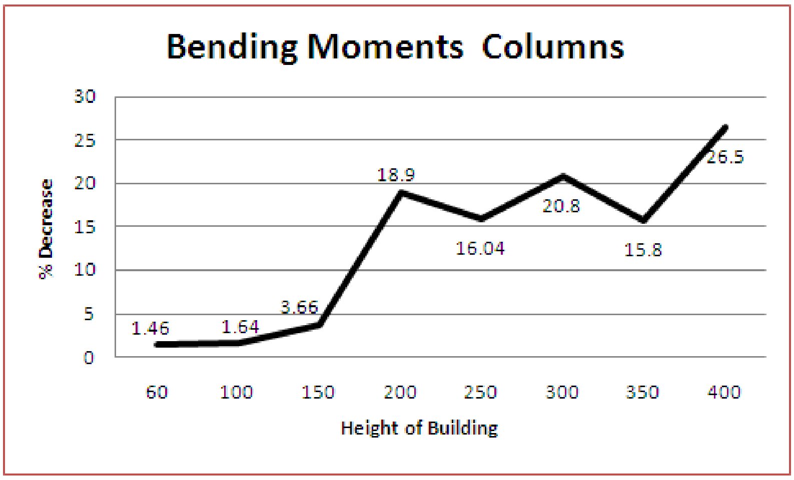

Fig. 10: Graph showing percentage decrease in bending moment of column Vs height of building

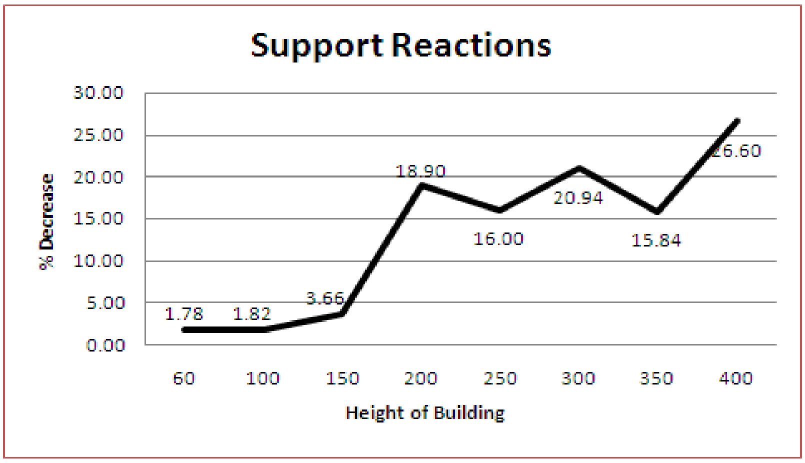

Fig. 11: *Graph showing percentage decrease in support reaction Vs height of building*

Height of Building	Avg. Decrease in Beam Reinforcement (%)		Avg. Change in Column Reinforcement (%)
	Negative Rein.	Positive Rein.	
60	2.6	Not significant	2.9
100	9.2	5.5	3.5
150	16.4	33	4.6
200	35.6	50	38.8
250	37.6	47.5	34.5
300	40.1	50.98	23.4
350	35.5	43.3	19.2
400	39.8	52.15	40.6

Table 3*: Summary of comparison of reinforcement area requirements in static and dynamic analysis*

7. Discussion of results

It is evident from the work presented that the vibration parameters of structure responding to an earthquake, depends upon the method of calculating the seismic force distribution within the structure. Equivalent static lateral force method gives member forces and displacements of the structure larger than the more precise Response Spectrum analysis.

This difference in the analysis results, which obviously affects the structural design of the buildings, increases with the increase in height of the building.

Requirement of reinforcement can be reduced on the basis of Response Spectrum Analysis which consequently reduces the budget required for the building.
Support reaction is reduced up to 18% resulting in economical foundation design.
The column and beam sizes where the required reinforcement is minimum in both static and dynamic analysis results, sizes of the members can be reduced on the basis of Response Spectrum Analysis results which show lesser stress in the members as compared to the static analysis.

8. Conclusions

- There is a significant reduction of about 31.3% in beam moments if Response Spectrum Analysis is performed instead of static analysis for 20 story building (200 ft height) or above in seismic Zone-3. This results in 35.5% decrease in negative reinforcement and 50% decrease in positive reinforcement area.
- Top story deflection is reduced up to 44% and more if Response Spectrum Analysis is performed instead of static analysis for 20 story building (200 ft height) or above in seismic Zone-3.
- There is a reduction of about 18.9% in columns sizes if Response Spectrum Analysis is performed instead of static analysis for 20 story building (200 ft height) or above in seismic Zone-3. This results in 38% decrease in column reinforcement.
- On the basis of Response spectrum analysis member sizes can be reduced (as compared in static analysis) which will further result in lesser dead weight of the structure and will result in an economical foundation design.
- Structure with 200ft height and higher should be designed on the basis of analysis results from response spectrum analysis and not by the static analysis to get an economical and safe structure.

9. REFERENCES

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